An Optical Load-extension Indicator, together with some Diagrams Obtained therewith.

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(Communicated by Sir J. A. Ewing, K.C.B., F.R.S. Received January 20,—
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The object of this paper is to describe an instrument by means of which load-extension diagrams of different materials may be obtained with precision, and to show some of the diagrams obtained therewith.

The majority of machines for testing the strength of materials are fitted with apparatus for the purpose of obtaining automatically load-extension diagrams of the specimens tested. In a common form of the instrument the diagram is drawn by a pencil or tracing point on a sheet of paper wrapped round a drum. The pencil is constrained so that it is only free to move in a direction parallel to the axis of the drum. The instrument can be attached to the frame of the machine, or to a support external to the frame. The pencil receives a motion proportional to the extension of the specimen through the agency of a fine wire carried over guide pulleys to clips fixed at a definite distance apart on the specimen, whilst simultaneously the drum receives an angular displacement proportional to the load applied to the specimen by means of a wire led over guide pulleys and fastened to the jockey weight.

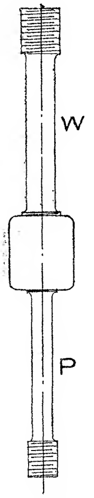

Fig. 1.—Weigh-bar and specimen in series.

The load-extension diagram obtained in this way is not strictly the load-extension diagram of the specimen under test, because the real load on the specimen is the load apparently applied by the jockey weight *plus* the effect of the inertia of the jockey weight and the beam. Any rapid change of load on the specimen as at the yield point is not truly recorded on the diagram. There are other ways of making the apparatus, but the diagrams obtained are in general subject to errors due to the inertia of the beam or the parts of the recording gear; to errors due to friction and to stretching of the cord; to errors due to relative movement between the instrument and the specimen.

The inertia effect of the beam and jockey weight is entirely eliminated by the use of a weighing bar placed in series with the specimen as indicated in fig. 1, where W represents the weigh-bar and P represents the specimen.

The load on the specimen is in this arrangement measured by the extension of the weigh-bar suitably magnified.

The cross-section of the weigh-bar must be so proportioned in relation to the cross-section of the specimen that the specimen breaks before the stress in the weigh-bar reaches the elastic limit of the material, in order that the straight line law between the load and extension of the weigh-bar may not be sensibly departed from before the specimen breaks. This condition limits the extension of a weigh-bar of 10 inches effective length to about two-hundredths of an inch.

The mechanical multiplication of the small extensions of the weigh-bar to the extent required to show them to a sufficiently large scale presents difficulties.

An instrument in which this mechanical multiplication was successfully accomplished was, however, designed by Sir Alexander Kennedy and the late Prof. Ashcroft, and an account of it by Sir Alexander Kennedy, together with some diagrams obtained, will be found in the discussion of a paper in the 'Proceedings of the Institution of Mechanical Engineers,' 1886, entitled "Autographic Test-recorders," by Mr. J. H. Wicksteed.

In the instrument designed by the author, the inertia of the beam is eliminated by the use of a weigh-bar, as in Prof. Kennedy and Prof. Ashcroft's instrument, but the magnification of the extension of the bar is done optically, and the diagram is obtained photographically, thus eliminating pencil and other sources of friction. The extension is measured at the axis of the bar, which is bored out to take the necessary apparatus, thus eliminating errors due to unequal extension and bending.

Description of the Instrument.—The instrument (fig. 2) consists of (*a*) a weigh-bar W; (*b*) the optical apparatus for magnifying the extension of the weigh-bar; (*c*) the optical apparatus for projecting the extension of the specimen on to the photographic plate, together with the mechanical apparatus connecting the mirror lever with the specimen; (*d*) the illuminating apparatus; (*e*) the camera.

A special feature of the instrument is that the camera, the optical apparatus and the illuminating apparatus are attached to the weigh-bar, and have no contact with the frame of the machine or with any support external to the frame, so that the diagram is unaffected by any straining action in the frame itself, or by any relative movement between the specimen and the frame.

A diagrammatic arrangement of the instrument is shown in figs. 2 and 3. The ends of the weigh-bar W are screwed, and it is bored out to take the optical apparatus for magnifying the extension.

A small concave mirror M is mounted on a frame carrying three hard steel points. The line joining the points 1 and 2 is the axis about which the mirror is free to turn. A light steel tube *t*, pointed at the lower end to rest in the cone formed at the bottom of the bar, and coned at the top to take the point 3 of the optical lever, is kept in position by the spring *s*, fig. 3.

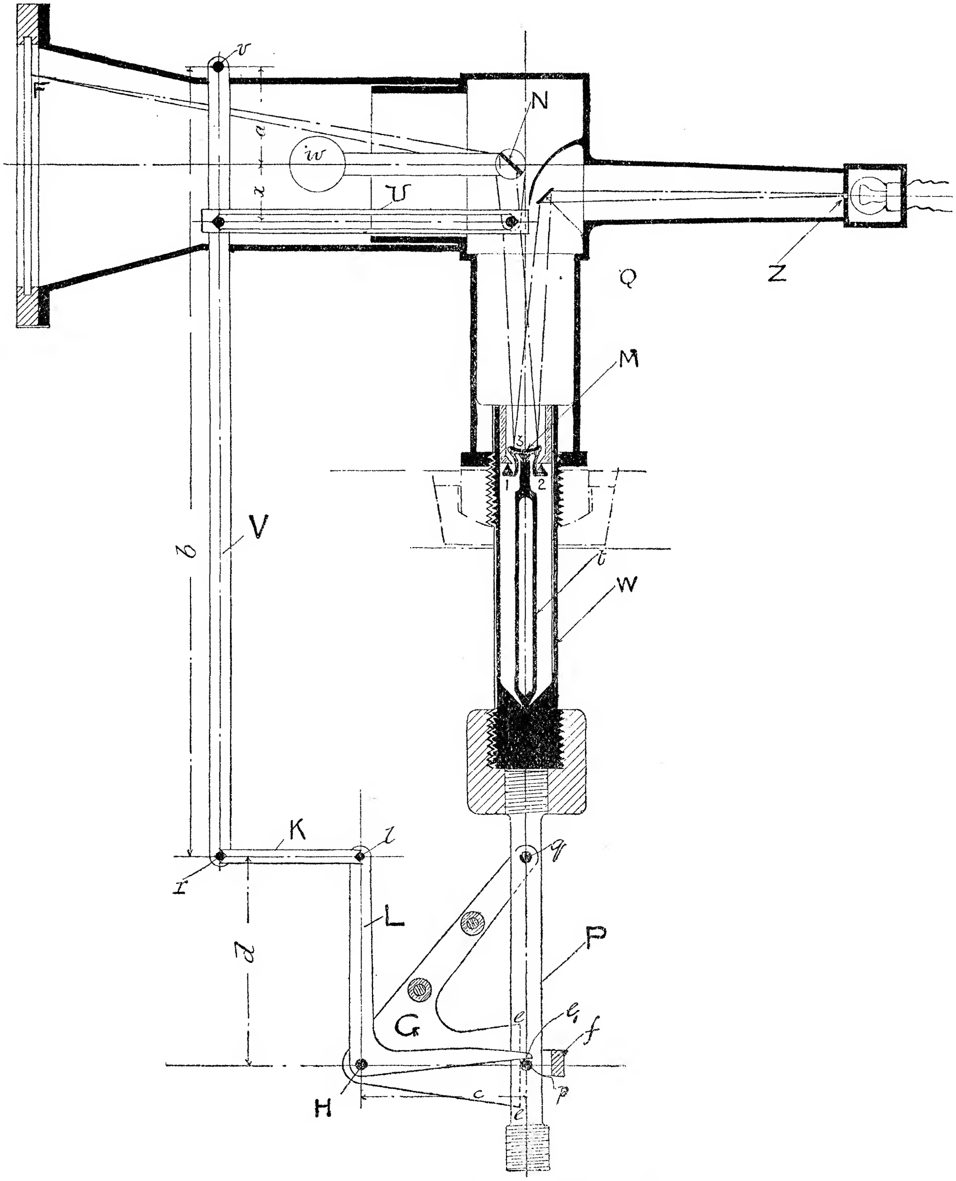

Fig. 2.—General arrangement of indicator in section.

The extension of the weigh-bar tilts the mirror M through an angle x/l, where x is the extension and l is the length of the arm of the optical lever.

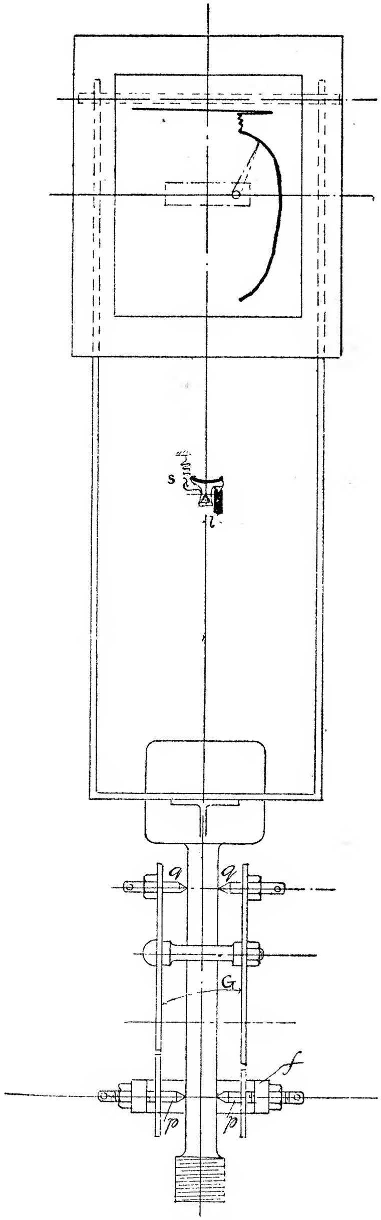

FIG. 3.—End elevation.

A beam of light starting from the source Z is reflected by the fixed mirror Q on to the mirror M, from which it is reflected to the mirror N, and from N it is brought to a focus on the photographic plate F. The source of light Z and the focus at F are conjugate with respect to the mirror M.

It will be understood from this that the spot of light focussed on the plate moves horizontally across the plate as the weigh-bar extends. In the actual apparatus the dimensions are such that the spot moves 340 times the actual extension of the bar, so that an extension of 1/100 of an inch corresponds with a movement of the spot of 3·4 inches horizontally. This horizontal movement is proportional to the load actually applied to the specimen through the weigh-bar W.

The mirror N is carried on an axis placed at right angles to the axis 1 2 about which the mirror M turns.

The axis of N is connected to the specimen P by a linkage which ensures that the angular movement of N is proportional to the extension of the specimen P between the gauge points q and p.

The points of two steel screws, p, p (fig. 3), carried by a frame f, are forced into the specimen and are held in place as the diameter of the specimen contracts, by the spring of the frame f.

A frame G is attached by similar pointed screws, q, q, to the specimen at a parallel diameter 5 inches above the lower points, p, p, and the spring of the side plates of the frame maintains the points of q, q, in contact with the specimen as the diameter contracts. This frame G is free to turn about the axis qq, and it does so until its vertical edge *ee* (fig. 2) finds contact with the turned part of the lower screws, *p*, *p*, and contact is maintained by the weight of the frame itself.

Thus the lower frame *f*, carrying the pointed screws, *p*, *p*, is not directly connected with any other part; but the turned surfaces of the screws, *p*, *p*, near the point provide surfaces against which the vertical edges *ee* of the frame G rest.

The frame G is provided to carry an axis H for the bell-crank lever L so that, as the specimen extends, the axis H remains at a fixed distance *c* from the centre line of the specimen.

A bell-crank lever L is free to turn about the axis H. One arm rests on the pin *p* and follows it as the specimen extends, contact being maintained by the weight *w* above acting through the linkage, whilst the other arm is connected by a link K to the end of a hanging lever V which is free to turn about the axis *v*.

This hanging lever V is so long relatively to the displacement of its end *r*, that the path of *r* is practically a straight line.

The coupling link K therefore corrects the circular movement of the axis *l* to a linear movement of *r* proportional to the movement of the point of contact e_1 between the bell-crank and the pin *p*, which contact point moves in a straight line without sensible error.

The coupling link K serves also another purpose, namely to prevent the extension of the part of the apparatus above the upper gauge point *q*, *q*, and the upper support of the weigh-bar from being recorded on the plate. The extension of the part above *q*, *q*, has the effect of displacing the fulcrum H vertically by an amount equal to the elastic extension of the weigh-bar and the extension of about 1 inch of the specimen above the axis *qq*. This vertical displacement of H downwards merely turns the link K about the axis *r* and produces no sensible horizontal movement of *r*, and therefore the vertical displacement of H is not recorded on the plate.

The lever V is connected to an arm clamped on the mirror axis by the coupling rod U, so that the angular displacement of the arm V is communicated to the arm on the mirror axis without sensible error.

Contact at all points through the linkage is maintained by the weight *w*, which is carried by an arm clamped to the axis of the mirror, and it thus exerts a constant turning moment on the arm and maintains a constant pressure at all points of the linkage down to the final point of contact between the arm of the bell-crank lever and the lower axis, *pp*, at e_1.

The linkage thus converts the vertical extension of the specimen between the gauge points *p*, *p*, and *q*, *q*, into a proportional horizontal displacement of the point *r* without sensible error, and the consequent angular displacement of the hanging lever is communicated to the arm on the axis of the mirror M, suitably changed in magnitude so that the full range of the spot of light on the plate corresponds to the full extension of the specimen between the gauge points.

When the specimen breaks, the bottom frame *f*, with the screws *p*, *p*, still gripping the specimen, drops away with the lower part of the specimen. A stop limits the motion of the arm carrying the weight *w*.

There is geometric contact at all the link joints. When the apparatus is set up and the spot of light is brought to some convenient zero on the ground-glass focussing plate of the camera, the linkage may be displaced in any way and the spot always comes back to the zero with a snap as the point of contact e_1 is made.

This linkage has the valuable property that the movement of the spot of light can be accurately calibrated *in situ*. This is done by means of a calibrating step gauge like a ladder with steel rungs set accurately at half an inch apart. When the apparatus is set up and an experiment is about to begin the spot of light is brought to a convenient zero. The step gauge is placed on one of the lower pins *p*, *p*, and the frame G and with it the bell-crank lever is drawn slightly away from the specimen and then replaced, but with the end of the bell-crank lever resting not on the pin *p* but on a pin in the step gauge half an inch below it. The corresponding movement of the spot of light may then be observed directly on the focussing plate, or if a photo record is to be taken a slight movement of the jockey weight on the beam produces a slight displacement of the spot at right angles to the extension axis of the record, and thus when the plate is developed an index mark appears at a distance from the origin corresponding to a half-inch movement of the point of contact e_1 in a vertical direction. The plate may be calibrated in this way at half-inch intervals, or even quarter-inch intervals, if desired. In practice, however, it is only necessary to obtain one or at most two such marks, because the movement of the spot is proportional to the extension of the specimen without sensible error, and a full scale

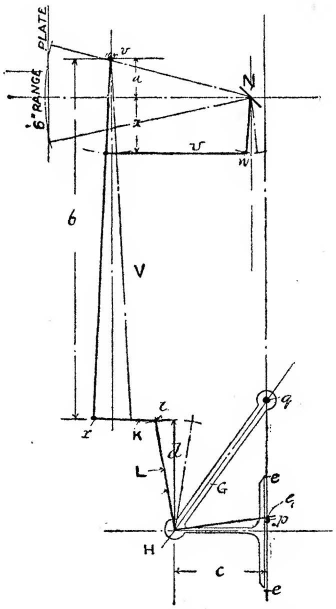

Fig. 4.—Centre line sketch of extension linkage.

can be constructed from the marks obtained *in situ* after the diagram is developed.

Another convenient property of the linkage is the ease with which the scale of the diagram may be changed. This will appear from a consideration of the dimensions of the linkage. Referring to the centre line diagram of the linkage in fig. 4 it will be observed that the maximum range of the spot of light is 6 inches. The focussing plane is about 12 inches from the mirror N, hence a range of 6 inches corresponds with an angular movement of the mirror of a quarter of a radian. Let x be the length Nn of the arm fixed to the mirror shaft, and let h be the horizontal displacement of its end, then the spot has passed over its full range when

$$h/x = \tfrac{1}{4}. \qquad (1)$$

Let l be the extension of the specimen between the gauge points; c and d the lengths of the arm of the bell-crank lever; b the length of the hanging lever V, and $(a+x)$ the distance from the axis of V to the point at which the coupling rod is attached. Then

$$h = \frac{d(a+x)l}{bc}, \qquad (2)$$

which by the aid of (1) gives

$$x = \frac{d}{c}la \bigg/ \left(\frac{b}{4} - \frac{d}{c}l\right), \qquad (3)$$

from which the magnitude of x can be calculated in order that an extension l between the gauge points may produce a movement of the spot of light over the whole range of 6 inches.

In the actual instrument

$a = 3$ inches, $b = 22{\cdot}9$ inches, $c = 4$ inches, $d = 5{\cdot}625$ inches,

so that

$$x = \frac{4{\cdot}218\,l}{5{\cdot}725 - 1{\cdot}406\,l}. \qquad (4)$$

Let the total extension to be provided for be 2 inches. Then, inserting 2 for l in (4), $x = 2{\cdot}9$ inches, that is to say, an extension of 2 inches will produce a movement of the spot over the full range of 6 inches.

The arm and the hanging lever V, coupled by the rod U, are slotted, so that an adjustment of x can be readily made without disturbing any other part of the apparatus.

An exact adjustment of x is not necessary, because every diagram is calibrated for extension when the specimen is *in situ,* and just before the load is applied to the specimen, in the way explained above.

Method of Making a Test.—When the specimen is in place and the apparatus set up, the first step is to bring the spot of light to the point on the focussing plate which is to be the origin of the diagram. This can be easily and quickly done by means of the adjustment provided. Then, after the plate has been inserted in place, the beam is balanced at a moderate load, usually about half a ton. The step gauge is then inserted between the end of the bell crank lever and the lower points, p, p, and two or three lines drawn on the plate at known distances from the origin in the way explained above. The beam is next carefully balanced at 1 ton, and, when it is standing midway between the stops, and quite free from vibration, the hanging lever V is drawn back and replaced, in order that the spot of light may move over the plate in a direction parallel to the extension axis, and thus fix a line in the load scale corresponding to 1 ton. The load scale, photographed on a separate plate, is afterwards applied to the photographic record, so that the lines marked 1 ton on each coincide, in order to read off the load corresponding to any point on the diagram.

After drawing the 1-ton line the lever is dropped to the lower stop, and the jockey weight is run out to 12 tons. The load is then applied to the specimen by starting the hydraulic ram connected with the straining cylinder, which is kept going until the specimen breaks.

If the specimen requires more than 12 tons to break it, the beam lifts, and thus prevents the weigh-bar from being overstrained. In fact, the beam and the jockey weight may be regarded as a safety device, to show when the load applied by the straining cylinder exceeds the maximum load for which the weigh-bar is designed.

The load scale of the apparatus is shown by photo. fig. 5. It is obtained by connecting the weigh-bar to the bottom shackle of the machine, and then balancing the beam at a series of loads and at each load giving the mirror axis N a small angular displacement by hand. The instrument is shown in position in the testing machine, with a specimen attached to the weigh-bar, and with the extension apparatus in place, in fig. 6.

Diagrams Obtained with the Instrument.—A typical diagram for a piece of mild steel is shown in fig. 7. The load at any point is obtained by placing the load scale of fig. 5 over the diagram so that the 1-ton lines coincide. The extension scale is fixed by the ½-inch calibration marks obtained by the step gauge.

It will be seen from the diagram that the load rises to a maximum value of 6¼ tons and then drops back to about 5·4 tons. The metal then draws out with small variations of load until at an extension of 0·12 inch the curve becomes smooth and rises to the maximum load of 8 tons. After this the curve drops smoothly to the point at which fracture takes place. This point is well defined in the diagram, because at the instant of fracture

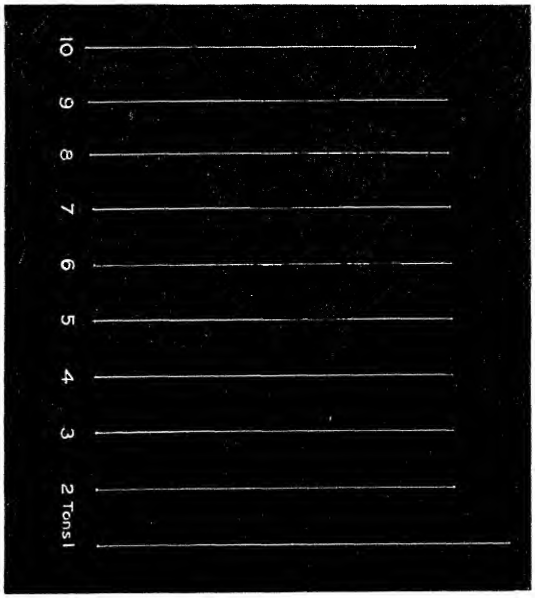

FIG. 5.—Photograph of load calibration.

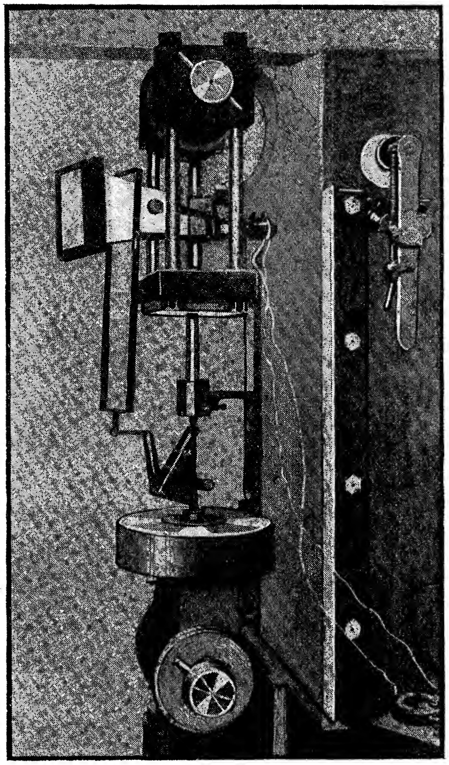

FIG. 6.—General view of indicator in the testing machine.

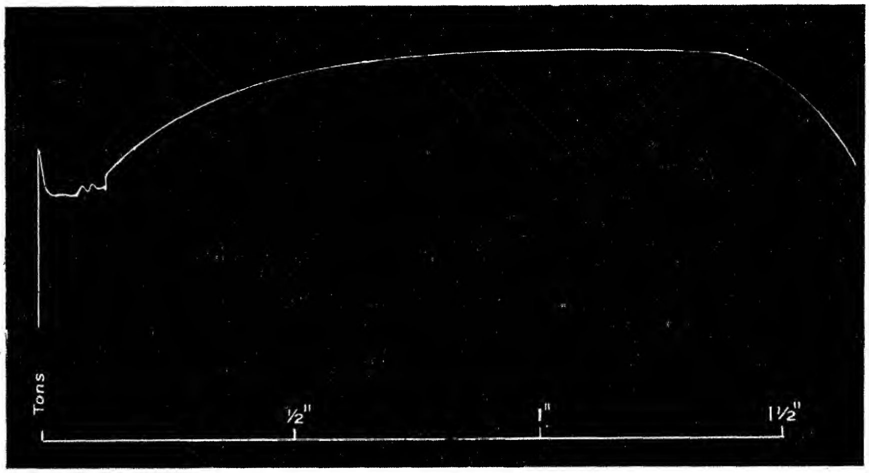

FIG. 7.—Load-extension diagram of mild steel.

the spot of light starts to move so rapidly that no impression is made on the plate.

The time occupied in breaking the specimen was three minutes, approximately.

The extension of the specimen measured 1·64 inches on a gauge length of 5 inches, with a reduction of area at the fracture of 64 per cent.

The total extension scaled from the diagram is also 1·64 inches.

In order to get some idea of the time occupied by the successive characteristic phases of the break, a mild steel specimen turned from the bar from which the specimen whose load-extension diagram shown in fig. 7 was cut was broken by steadily working the ram and thus steadily increasing the strain, and the spot of light was followed on the ground glass focussing plate with a pencil, and the times at which the spot arrived at different points on the curve were recorded by means of a chronograph, the key of which was placed close to the machine so that it could be operated with one hand whilst the point could be marked on a plate with a pencil in the right hand.

The total time of the break was increased to about six minutes in order to get a better idea of the relative time occupied in the parts of the curve where the movement of the spot is most rapid.

The general characteristics of the diagram as regards time are as follows:—The spot moved steadily from *a* to the point of maximum load *b* (fig. 8) in 50 seconds, and then dropped to the point *c* in a time estimated at a quarter of a second, and then moved along the irregular path from *c* to *d* in about

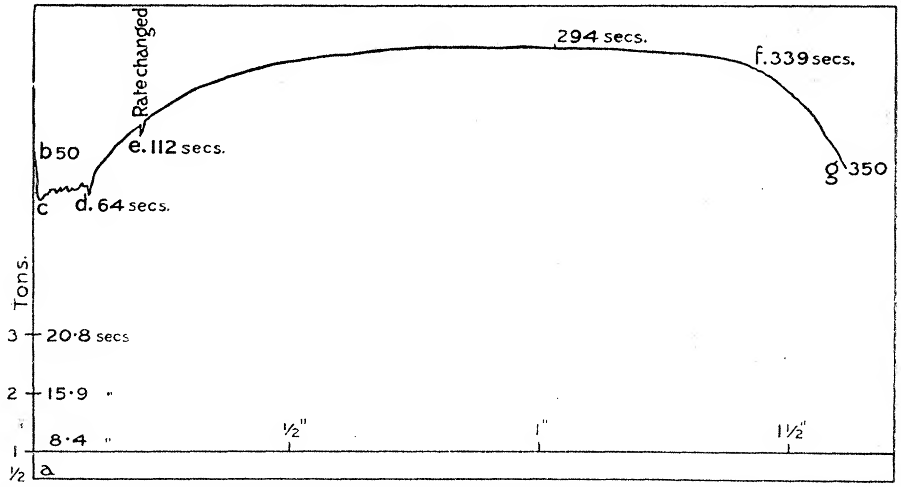

Fig. 8.—Giving times at which spot passed various points in a load-extension diagram of mild steel.

fourteen seconds. When the spot arrived at the point *e* the rate at which the specimen was extended was increased to the same rate as that used in connection with the load-extension curve shown in fig. 7. The time at which the spot passes the point of maximum load is shown against the curve in the diagram. To an observer the spot appears to move with uniform speed along the curve from *e* to *f*, and then to quicken gradually towards the point of fracture *g*.

The sudden drop from the maximum elastic load carried by the specimen to an indefinite relation between the load and the extension and the subsequent definite relation during the plastic yielding characterises all the diagrams which were taken of mild steel and iron, as will be seen in the diagrams shown in fig. 10. With copper, however, there is no complicated relation at the yield point. The passage from the elastic state to the plastic state is pretty sharply defined, as will be seen from fig. 9, which is the load-extension diagram of a piece of copper containing 0·295 per cent. of arsenic.

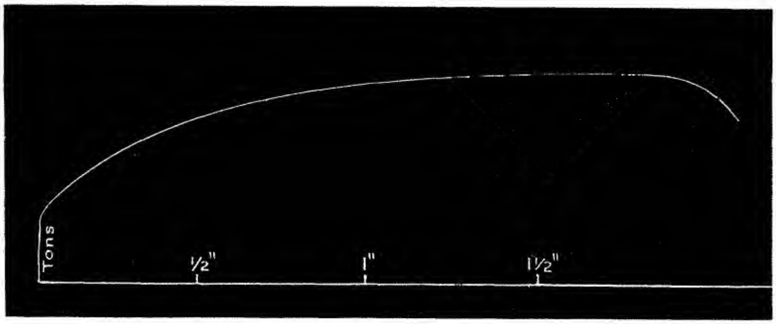

Fig. 9.—Load-extension diagram of copper.

Load-extension diagrams of a series of three steels containing increasing percentages of carbon have been taken, and also a diagram from a piece of Farnley iron. All the diagrams are shown in fig. 10 reduced to a common load scale and to a common extension scale for purposes of comparison.

The extreme points of the curves shown in the photographs are well defined, and therefore the actual loads on the respective sections at the instant of fracture can be measured off the diagrams with accuracy. The stress calculated from the actual load and the fractured area measured from the broken bar is calculated for each of the specimens shown in fig. 10 and it is plotted vertically above the extreme point of each diagram. The chain-dotted curve connecting these points with the respective regions of maximum stress is sketched in roughly to indicate the form of the load-extension diagram at the particular section at which fracture occurred.

Thus in the case of the uppermost curve the maximum load carried was 42 tons per square inch, and the load on the fractured area was 61 tons per square inch.

The three steels shown in fig. 10 have approximately the same percentage composition as regards silicon, sulphur, phosphorus, and manganese, but have different percentages of carbon. With the exception of copper the extensions were taken on a gauge length of 5 inches. The copper specimen was gauged on $4\frac{1}{2}$ inches.

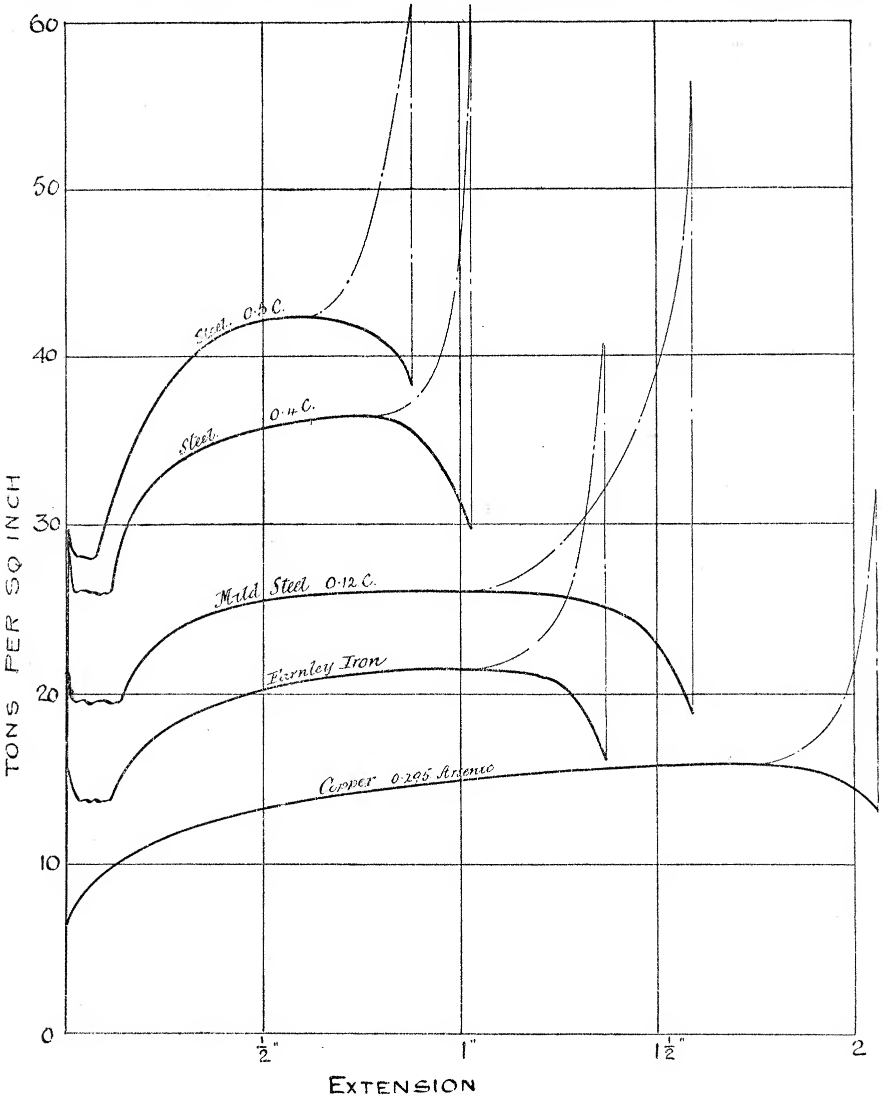

FIG. 10.—Load-extension diagrams reduced to common scales of load and extension.

These diagrams are shown in order to indicate the possibilities of the instrument. It is proposed to make a series of tests on the various kinds of metals used in the industries particularly with the object of investigating the region immediately beyond the elastic limit and the effect of suddenly applied loads and loads applied very gradually. The characteristic of the method of applying the load in all the diagrams shown is that the rate at which the extension of the specimen increases is approximately constant, because the pressure is applied to the straining cylinder of the testing machine by a ram driven in at a nearly constant rate. The rate at which the load is applied is therefore variable, as will be understood from fig. 8. The scale of the extension can in the particular instrument described be magnified conveniently about eight times, so that it is only suitable for investigations outside the true elastic region. The author hopes to communicate a paper shortly giving the description of a similar instrument for obtaining automatic diagrams within the elastic region.

The Passage of Homogeneous Röntgen Rays through Gases.

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of North Wales, Trinity College, Cambridge.

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Introduction.

The phenomena attending the passage of Röntgen rays through gases has been examined by several experimenters. The relative ionisation produced in different gases was investigated early in the history of Röntgen rays by Perrin* and Rutherford,† and later by Sir J. J. Thomson,‡ Strutt,§ McClung,|| Eve,¶ Barkla,** and Crowther.†† Some of these experimenters

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* Perrin, 'Ann. de Chimie et de Phys.,' 1897, vol. 11, p. 496.

† Rutherford, 'Phil. Mag.,' 1897, vol. 43, p. 241.

‡ J. J. Thomson, 'Camb. Phil. Soc. Proc.,' 1900, vol. 10, p. 10.

§ Strutt, 'Roy. Soc. Proc.,' 1903, vol. 72, p. 209.

|| McClung, 'Phil. Mag.,' 1904, vol. 8, p. 357.

¶ Eve, 'Phil. Mag.,' 1904, vol. 8, p. 610.

** Barkla, 'Camb. Phil. Soc. Proc.,' 1909, vol. 15, p. 257; 'Phil. Mag.,' 1910, vol. 20, p. 370.

†† Crowther, 'Roy. Soc. Proc.,' 1908, vol. 82, p. 103.

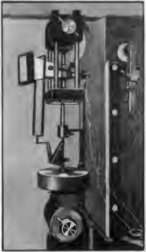

FIG. 6.—General view of indicator in the testing machine.